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Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand

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ABSTRACT

By extensively reviewing the current state of knowledge, this paper explores the sustainability implications of palm oil biodiesel in Southeast Asia, with a focus on Indonesia, Malaysia and Thailand. Both ecological and environmental vitality as well as socio-economic equity are emphasized in the authors' exploration of sustainability in the three country cases. The article observes that the main environmental sustainability considerations of palm oil biodiesel include its capacity to reduce carbon dioxide emissions, its carbon debt and its repercussions on forestry, biodiversity, and soil and water quality. Issues surrounding socio-economic sustainability encompass how palm oil biodiesel affects food security in Southeast Asia, along with the impact of palm oil production on rural livelihoods and land-tenure. The authors firstly explore the origins, drivers and current technologies surrounding palm oil biodiesel development in the region. They then present the three country cases in order to concentrate on the particular policies, challenges and opportunities that uniquely impact the sustainability of biodiesel development in each locale.

Contents

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1. Introduction

Extending universal access to energy in developing economies and mitigating human-induced climate change are two of the most critical issues facing the world today. Compounding these issues, volatile prices for fossil fuels are undermining energy security and eroding balances of payments by escalating the cost of energy imports. As part of their response to these convergent trends, many governments across the world are promoting biofuels – namely ethanol derived from plant-based starches and sugars, and biodiesel derived from oil crops and animal fats. In 2012, some 106 billion liters of biofuels were produced globally, of which 22.5 billion liters were in the form of biodiesel [1].

The growing global market for biodiesel, and its close cousin, bio-jet fuel (aviation biofuel), has created opportunities for several countries in Southeast Asia that find themselves poised as major producers, consumers, and exporters. For export-oriented nations such as Malaysia and Indonesia, biodiesel production has proceeded through large agribusinesses enterprises. For example, in 2011, Indonesian biodiesel exports ballooned to 1.2 billion liters, a 117% growth over 2010 [2]. This growth has encouraged the national government to allocate 20 million hectares of land towards establishing new oil palm plantations, which represents a 330% increase over present land area under cultivation [3]. By contrast, in Thailand 100% of the national production is directed towards domestic consumption and exports are actively discouraged by the government that does not issue export permits for pure biodiesel (B100) [4]. However different their inspirations for biodiesel production may be, these three countries stand united in their choice of palm oil as a dominant first-generation feedstock [5,6]. The oil palm has flourished as an economically vital crop in the region given its use as both food and fuel. Also multiplied as a consequence, however, are the numerous environmental and socio-economic impacts arising from palm oil production.

This paper analyzes palm oil biodiesel in Southeast Asia, with a particular emphasis on Indonesia, Malaysia and Thailand. While Indonesia and Malaysia have historically been the main forerunners of palm oil in the region, the case of Thailand is also included for the interesting contrast it provides as the newest and third largest producer. The review attempts to distil the current state of knowledge surrounding the associated sustainability implications of the first generation biofuel derived from palm oil.

In differentiating between ‘first’ and ‘second’ generation biofuels, this article follows the definitions provided by the International Energy Agency (IEA). By ‘first’ generation, the article implies those biofuels produced from food-crops including oil-seeds and grains and by ‘second’ generation biofuels, we mean ligno-cellulosic feedstock including straw, bagasse, forest residues and “purpose-grown energy crops such as vegetative grasses” [7–9]. By ‘sustainability’, the authors wish to emphasize both long-term ecological viability and socio-economic equity considerations.

The study begins with a discussion on why the palm oil has been considered to be advantageous as feedstock for biofuels such as biodiesel and jet fuels. The article notes that the primary environmental sustainability dilemmas of palm oil biofuels include its disputed potential to mitigate greenhouse gas (GHG) emissions, its carbon debt implications as well as its impacts on forestry, biodiversity, and soil and water quality. Socio-economic sustainability concerns are explored next with an emphasis on how palm oil biodiesel affects food security in Southeast Asia, along with rural livelihoods and land-tenure issues. In the second part of the paper, Indonesia, Malaysia and Thailand are presented as specific cases. That discussion investigates the policies that have been adapted to encourage palm oil biodiesel in each country, the sustainability constraints that remain, and how they can be addressed.

2. Methods

To collect data for our study, a systematic and extensive search was conducted for peer-reviewed academic articles published in the 2000–2010 period, in addition to information provided by government and market-research sources. A secondary review was completed in 2012 as an update. The search proceeded for several sets of keywords in titles of articles appearing in eight different academic databases. Total number of articles considered for each database included: Science Direct (139), JSTOR(53), Project Muse(8), Hein Online(38), SpringerLink (149), Taylor & Francis (16) and EBSCOhost (77) and Econlit (2), including the keywords “oil palm and biodiesel”, “oil palm and sustainability”, “biodiesel and sustainability”, “oil palm and technology”, “biodiesel and technology”, “oil palm and policy”, “biodiesel and policy”. Results were filtered for those relevant to Asia. Only those articles with an explicit topical focus have been directly cited and referenced in this paper for brevity.

To supplement these peer-reviewed studies, policy literature and data from national ministries, major international research institutes and multilateral development banks have been included in order to span an array of publically reviewed statistics and information. The use of these different resources allowed for triangulation and ensured a mix of perspectives. The issues presented in the paper are applicable generally across all fuels that are derived from palm oil.[2] However, a particular emphasis has been put on palm oil-based transport biodiesel as it is the most commercially advanced in the context of the three Asian cases explored in this paper.

3. Dynamics of southeast Asian palm oil

Owing to its suitability to regional climatic conditions and high yield rates, the oil palm is currently the main biodiesel feedstock in Southeast Asia. Ever since its introduction to the region in the 14th century, the oil palm has become a vital agricultural commodity, especially in Malaysia and Indonesia which have dominated regional production since the mid-1960s [10]. According to the Food and Agriculture Organization of the United Nations (FAO), these two nations are global palm oil giants, accounting for more than 80% of total world production. Indonesia is currently the leading palm oil producer in the world manufacturing a yearly 25 billion liters.

With its long-established history of cultivation and the resulting global comparative advantage, palm oil was considered as the natural first choice for producing biodiesel in Asia when technical feasibilities and new trade opportunities became apparent in the mid 2000s. Mostly used as a source of cooking oil and food supplement, the oil palm far surpasses other oil crops in terms of productivity with yield estimates ranging from 4 to 5 metric tons of oil per planted hectare (MT/ha). Other oilseeds have shown far lower yields, such as rapeseed (1 MT/ha), soybean (0.375 MT/ha) and sesame (0.16 MT/ha) [6,10–13]. Additionally, with production costs lower than those of other oil crops, palm oil enjoys a high rate of return on land, labor and manufactured capital [6,10]. With perennial yields, employment opportunities are available year-round on palm oil plantations that are thus viewed as an important vehicle for rural development in major producer countries such as Indonesia and Malaysia [14]. Climatically, conditions in Southeast Asia are optimal for growing oil palm, which thrive at temperatures between 24 and 30 °C and in areas receiving yearly

[2] Crude palm oil (CPO) can be used for fuel in steam-generating boilers, or mixed with middle-distillate fuels to form bio-kerosene and ‘drop-in’ fuels like bio-jet fuels, which have been explored as a substitute for aviation fuels.

precipitation levels of 1780–2280 mm [10]. By, the mid-2000s, palm oil had became the most extensively traded vegetable oil globally, driven by demand from importing nations such as India, China and the members states of the EU [10].

3.1. Major environmental sustainability considerations

The surge in the use of palm oil for biofuel has been paralleled by a growing concern over its uncertain carbon benefits and deleterious impact on ecological sustainability. The initial global enthusiasm for biofuels was based on assumptions of carbon neutrality which postulated that the carbon dioxide (CO_2) released during fuel combustion matched the CO_2 sequestered by the feedstock during its growth. However, this assumption has since been shown to be an oversimplification when due consideration is given to the energy requirements for the entire chain of biofuel production from feedstock cultivation, processing, fuel conversion, transport and eventually, combustion [15]. Additional relevant carbon measurements involve accounting for land use changes based on what former vegetation is displaced by feedstock plantations, the CO_2 that is emitted during soil tillage and from fossil fuel-powered agricultural machinery and the type and concentration of fertilizers that are used [16,17]. The latter is an especially vital factor of the carbon suitability of biofuel feedstock given that the nitrous oxide (N_2O) associated with certain fertilizers has a global warming potential of about 300 times more potent than CO_2 [18].

Two methods have been employed thus far to factor in these different variables in order to arrive at truer estimates of the emission reducing benefits from the production and use of biodiesel. First, for any particular type of biofuel, a Life Cycle Assessment (LCA) can be conducted that calculates the emissions at each of the different phases of the production to consumption pathway to ultimately arrive at a sum total of net emission reduction or gain. The LCA is usually performed according to guidelines specified by the International Organization for Standardization (ISO) standard ISO14044:2006. Second, a method of calculating "carbon debt" [16,19] specifically considers the carbon emissions that result from clearing land (both directly and indirectly) for growing feedstock and the time it would take for the resulting biofuel to negate or "repay" that debt and achieve emission reductions relative to fossil fuels. The use of both of these methods in the context of palm oil biodiesel is discussed below.

3.1.1. Greenhouse gas (GHG) emissions

One method for gauging the comparative carbon benefits of using bio- versus fossil fuels involves conducting a comprehensive analysis of GHG emissions at every stage of the fuel's life. The resulting LCA provides a cradle-to-grave analysis of net carbon emissions from the fuel's production phase to its ultimate combustion and has been used as a tool for comparing the emission reducing merits of various biofuel feedstocks including Southeast Asian palm oil [16,19–21].

Emission reduction figures derived from the LCA method vary widely. Many LCA studies of palm oil biodiesel so far have pointed out that with business-as-usual cultivation and production practices, emissions may be comparable to those from fossil fuels [16,22–24]. More recently, studies by Searchinger [17] and Haberl et al. [17,25] indicate that if LCA analyses were to include the biofuel's emissions during combustion, this amount can only be offset by growing biomass additional to the one used to produce the fuel [25]. On the other hand, several other studies are unwavering in their recommendation of palm oil biodiesel [13,20,21,26].

A recent meta-analysis performed by Souza [26] of palm oil biodiesel LCA studies undertaken over the last decade indicates a wide diversity in the estimates of greenhouse gas emissions. Numbers range from 1901 kg of CO_2 equivalent per hectare per year (kg CO_2 e/ha/year) [26] to 4238 kg CO_2 e/ha/year [20]. The discrepancy in results is attributed to the diverse scopes of analysis. Contextually different, each study first defines a system boundary that delineates the processes that are included in the analysis. The system boundary specifies the 'cradle' and the 'grave' demarcating the scope, which varies by analysis. Some authors have employed a "seed to factory gate" [26] scope, while others use a "plantation to production plant" boundary [20], and yet others have used a "plantation to end-use vehicle" approach [27]. It is estimated, however, that land use changes associated with the palm oil cultivation stage are the greatest determinant of the resulting biofuel's lifecycle emissions [16].

There is consensus among scholars that major improvements in emissions of GHGs and other pollutants can be achieved (i.e., emissions can be lowered) if the co-products of CPO processing can be put to use [20,28]. As illustrated by major international research endeavors [10] undertaken over the last decade, a rich discussion has propagated amongst academics and experts concerning the pollution-mitigating and profit-maximizing impacts of using oil palm byproducts such as the shells of empty palm kernel husks, process effluents and palm fiber. Empty kernel husks can be used as mulch and soil fortifiers in plantations while palm fiber can be used as a source of energy for oil mills [13]. Ash residue and dry shells from CPO processing can be used as boiler fuel as well as for construction and infrastructure support [29,30], palm wood can be used to make furniture [31] and empty kernels can be processed into paper, fiber board, compost and can be used for medicinal purposes [32,33]. Furthermore, biogas can be generated from palm oil mill effluent (POME) that can also help to reduce emissions during the fuels GHG emission life cycle, serving a double dividend of displaced methane emitted and increased local electricity supply.

3.1.2. Changes in land use

Both indirect as well as direct land use changes as a result of biodiesel feed stock cultivation can have severe implications on the fuel's emission profile. Direct emissions result when land is cleared and earmarked for biodiesel feedstock cultivation. Indirect land use change (ILUC) occurs when forests or grasslands are cleared for economic activity that is displaced by biodiesel feedstock production elsewhere. Unlike direct land use change, which can be readily observed, measuring ILUC must rely on modeling estimates given that indirect effects are often unpredictable, ambiguous and spread out because of the uncertainty associated with the carbon endowment of different land types and related carbon emissions from changes to their use [34,35].

Measuring ILUC from biodiesel has thus far used two main methods: equilibrium modeling using prices of land and commodities and causal descriptive modeling that relies on "comparing the (worldwide) land use when the biofuel feedstock is produced to the (worldwide) land use with no additional demand for biofuels" [34]. Emissions from land use change are typically measured in terms of carbon emitted per unit of energy produced. ILUC factors from oil-palm expansion in Indonesia and Malaysia can range from 5.9 to 82 Mg of CO_2 equivalent (CO_2e) per unit of energy or megajoule (MJ) of palm oil biodiesel burnt where the higher estimates are attributed to avoided coconut expansion and on plantations established in carbon-rich forests or peatlands and the lower values reflect changes made to grasslands and woodlands instead [34].

In their seminal article on the emissions impact of both indirect and direct land use change for biofuel feedstock cultivation,

Fargione et al. highlight the magnitude of carbon that is released by various oil palm growing methods, which lead to the resulting fuel incurring a carbon "debt" [16]. The authors base their life cycle assessment on current biogeochemical theory that ascribes three times more carbon storage to soil and plant biomass compared with the atmosphere. The scope of their assessment is essentially 'soil to final combustion'. They argue that "converting native habitats to cropland releases CO_2 as a result of burning or microbial decomposition of organic carbon stored in plant biomass and soils. After a rapid release from fire used to clear land or from the decomposition of leaves and fine roots, there is a prolonged period of GHG release as coarse roots and branches decay and as wood products decay or burn" [16] [p.1236]. Envisioning the quantity of CO_2 emitted in the first 50 years of this form of land-clearing as the "carbon debt" from land use change, the authors state that the resulting biofuels are eventually able to pay back this debt if their lifetime emissions are lower than those of the fossil fuels they replace. Therefore, "until the carbon debt is repaid, biofuels from converted lands have greater GHG impacts than those of the fossil fuels they displace" [16] [p.1236]. Following the methods used by Fargione et al., several contemporary studies have estimated the carbon debt of different biodiesel feedstock [19,36]. The most recent comparisons based on case studies done in Indonesia, Malaysia, Ghana, Mexico, Zambia and Brazil attribute the highest carbon debt (expressed as Mg of CO_2 per unit of land area) from direct and indirect land use change to oil palm plantations (472–1688 Mg CO_2/ha) [19].

The land use changes taking place in the oil-palm growing countries of Southeast Asia, particularly Malaysia and Indonesia, often involve the conversion of peat lands, which serve as some of the richest carbon sinks in the world. Peat soils, such as those of Malaysia and Indonesia, absorb carbon at the rate of 100 kg per hectare every year and are estimated to contain 20–33% of the Earth's terrestrial carbon [10,37,38]. Fargione et al. assess that close to a third of the new allowances for palm oil plantations in Malaysia and Indonesia are situated on peat-rich primary forests [16]. Owing to their rich carbon-storing capacity, their degradation results in an equally massive release of trapped carbon. Studies have shown that Indonesia represents 90% of the global carbon emissions from the burning of peat bogs [39]. The carbon debt that is therefore associated with burning of peat lands to make way for oil-palm plantations is indeed astronomical [36]. According to the study by Fargione et al., repaying the carbon debt from converting Indonesian and Malaysian tropical rainforests into palm oil plantations would take the resulting biodiesel 86 years [16]. The biodiesel produced from converting peat soils in these two nations, would require 423 years to repay its carbon debt or between 487 and 1743 Mg CO_2/ha [16,19]. Comparatively, soybean biodiesel has a carbon debt ranging from 57 to 574 Mg CO_2/ha, and jatropha biodiesel has a carbon debt ranging from 39 to 496 Mg CO_2/ha [19].

3.1.3. Forestry, biodiversity, soil and water Implications

Another environmental quandary surrounding palm oil biodiesel development in Southeast Asia concerns the conversion of rainforests into plantations and its associated repercussions on existing ecosystems. Some scholars and global institutions concerned with bioenergy recognize the environmental dilemmas that large-scale production of palm oil can present, by encroaching upon protected areas, affecting water systems, displacing food production and harboring unsustainable land-use practices that can not only nullify GHG emission benefits for decades, but also lead to widespread damage to ecology [40–44].

The natural forests of Indonesia, Malaysia and Thailand have long been regarded as one of the world's most biologically rich ecosystems. Yet these ecosystems currently face pressure from agriculture, industry and infrastructure development. Southeast Asia is unique in that 43% of its land area is covered with forests, and it has a diversified topography with mountains and 96,560 km^2 of coral reefs along with approximately 24,000 islands. The region has only 3% of the world's land, but 20% of all known species, including 25% of all known bird species. Indonesia and Malaysia both rank among the top 20 in terms of biodiversity and endemism (a term that describes when a species is unique to its location), and Indonesia itself is globally second for endemism and third for biodiversity. The region also has three of the world's 34 recognized biodiversity hotspots and of its known 64,800 species, 1312 are endangered [45].

Although forest conservation is undermined due to a variety of factors such as illegal logging and large scale land use changes linked with agriculture, the oil palm (and by association, palm-oil biofuels) continues to be heavily correlated with deforestation and the resulting impact on wildlife habitat due to fragmentation of previously contiguous forest areas [13,46–48]. Deforestation in Malaysia and Indonesia is linked to the decimation of ecosystems with rich biodiversity. Lowland tropical forests teeming with the highest concentration of insects, amphibians, reptiles and mammals are also considered to be the most suitable for large-scale oil palm cultivation because of rich soils, plentiful rainfall and marginal slopes [37,49,50]. The reduction of forests in Indonesia "has been associated with biodiversity loss, declines in the populations of iconic species (including Orangutan, the Sumatran tiger and the Indian elephant), forest fires and soil degradation" [37] [48,51]. Field studies in the region point out that conversion of secondary forests to oil palm plantations significantly diminish the quality of habitat for large mammals, and especially those most vulnerable and on the verge of extinction [52].

Even though the expansion of oil-palm plantations is linked with deforestation and the degradation of biologically sensitive habitat [47,51], the specific forestry impact from increased biofuel production from palm oil remains inconclusive. Scientists are able to forecast the effect on forests and biodiversity given historical and current rates of land conversion due to oil-palm cultivation [53]. However, plantations of oil palm are also spreading due to increasing food and industry demands, not only to provide feedstock for biofuels. Furthermore, part of the differences in the forestry impacts of oil-palm plantations derive from differences in the way that forest resources are defined by national governments. Contrary views exist, arguing that palm oil plantations should not be considered a driver of deforestation when compared to remaining natural vegetation, as plantations can themselves be considered forests [10]. Associating deforestation and biodiversity loss is even viewed as an "accusation" and a "general misconception" by some [54]. And many advocates are found to downplay the effects of increasing production of palm oil on biodiversity and forest cover. As Tan et al. ([54]: 424) put it "If deforestation and biodiversity loss are based on total forests available in a country… palm oil in Malaysia can be considered to be environmental friendly." [54]

Apart from biodiversity loss, the sheer scale at which palm oil is cultivated can damage soil and lead to water quality and availability problems. Soil erosion linked with clearing land to make way for palm oil plantations in Malaysia is estimated to amount to 8–4 t /ha/year [55] although this figure can be greatly reduced through better management practices [56]. Water quality has also been put at risk due to plantation practices in the region. For example, palm oil mill effluent (POME) has been disposed of as untreated waste into natural water sources in the past resulting in ecosystem health implications due to the severe degradation of water quality [10,57,58]. Furthermore, the general oil extraction

process is water intensive, as it demands large quantities of water, half of which gets disposed in the resulting POME [58]. Studies have shown that approximately 5–7.5 t of water are used in the process of producing 1 t of crude palm oil [59]. Additionally, almost 0.75 t of POME results from the processing of 1 t of fresh fruit bunches [60].

Furthermore, POME generally contains high levels of solid wastes, grease and wastewater that is acidic due to concentrated amounts of dissolved “protein, carbohydrate, nitrogenous compounds, lipids and minerals which may be converted into useful materials using microbial processes” [58]. Although measures to treat the waste emanating from processing has been put in place in the region, for instance in Malaysia, additional improvements and technology developments are necessary to address the issue at a more significant level [13]. Treatment of palm oil process waste can happen at several stages. Noted mechanisms of sediment and oil removal at the first stage of treatment can involve centrifugation, coagulation and filtration, aerobic or anaerobic digestion followed by processes of acidification and flocculation using chemicals such as aluminium sulfate and other organic compounds that remove the solid waste matter suspended in POME [61]. Secondary procedures such as membrane filtration and vermicomposting have also been expanded upon in recent reviews of POME treatment procedures [57–60].

3.2. *Main socio-economic sustainability considerations*

Growing in parallel with environmental concerns is the disquiet surrounding social and community impacts of biofuels. These include their impact on food prices, disadvantages for alternate businesses that are linked to palm oil, and as a drain on government budgets that subsidize palm oil biofuels [37]. As the foundations of oil palm run historically deep in Southeast Asia, the commodity has been largely perceived as having two roles in the region: one as a negative major catalyst of historic colonialism, yet another as a harbinger of contemporary economic development. The oil-palm sector in Malaysia, for example, is one of the country's main sources of employment [62]. Similarly, in Indonesia the oil palm sector provides jobs to 2 million people [51]. The oil palm is viewed as a significant source of economic development in the region, contributing steadily to national and province level GDP [36]. However, the social problems that have accompanied palm oil production through the past decades such as land grabbing from indigenous communities and the maltreatment of labor resources appear to have been worsened since the onset of biodiesel development in the last ten years. According to Obidzinski et al. ([36] p. 25) “In 2010 no fewer than 630 land disputes between palm oil companies and local communities had taken place in Indonesia” [36,63].

3.2.1. *Food versus fuel*

The ‘food versus fuel’ dilemma presents a constant sustainability quandary for palm oil biofuels in Asia, especially in view of the large regional dependence on edible palm oil [64,65]. Several factors contribute to the surge of palm oil prices. Below, market repercussions due to demand for the commodity for food and fuel are briefly explored.

Since 2006, the price of palm oil in Asia has suffered major fluctuations due to a surge in demand both domestically as well as at major export destinations [66]. By 2007, the biodiesel sector in the EU, the major destination for Asian palm oil, experienced a shortage of feedstock having diverted more than 60% of its rapeseed oil output (representing a quarter of total world production) [37]. As a result “of the diversion of rapeseed oil to fuel, EU imports of palm oil more than doubled between 2000 and 2006” [37,67]. This demand spike and speculative forecasting of future market activity resulted in palm oil prices swelling throughout the Asian region. According to Dillon et al. [37], in Asia “between early 2006 and early 2008, palm oil prices surged by around 165% – the price in January 2006 was RM 1412 ($384) and the price in March reached RM 4350 ($1182)” [37, p. 50]. Although high commodity prices benefit land-owners and palm-oil processors, they can be damaging to the livelihoods of the millions of usually poor households who are heavily reliant on palm oil for cooking. In Indonesia alone the demand for palm oil for food amounted to almost 3.7 million tons per year in 2008 and the high prices led to a significant surge in household expenditures on food [2].

In Southeast Asia as a region, higher domestic demand due to national biodiesel consumption mandates that are set to be implemented in the next five years are likely to necessitate production of palm oil on a much larger scale than the present, to meet both food and fuel needs. Since 2005, palm oil biodiesel has been greatly subsidized in Indonesia and Malaysia (the two largest producers) and it is likely that if consumption mandates proceed as projected, subsidies for the commodity will form a major part of government expenditure [37,49]. Most recently the competing demand of palm oil for food and fuel uses was felt in Malaysia. Mekhillef et al. [68] report that close to 40% of Malaysian palm oil has been set aside to produce biofuel, putting pressure on the remaining stock to fulfill vegetable oil demand [68].

3.2.2. *Smallholder production*

Smallholders constitute a major oil palm producer group in Southeast Asia. Smallholder farmers in the region typically own land holdings varying in size between 7.5 and 50 ha [69]. In Indonesia, these farmers generally own around 2 ha of land. Smallholders represent at least one third of the palm oil cultivated in Indonesia and Malaysia and an even higher proportion in Thailand [55,70]. One of the main issues facing smallholder farmers relates to low yields from their production systems in comparison to large plantations that are under private or government ownership and are able to achieve greater economies of scale. Some studies show that with adequate agricultural extension, better planting technologies and more accessible capital, they are able to equal the production rates of large-scale plantations [70]. However, yields can vary according to local conditions and depend upon factors such as availability of fertilizers and pesticides and efficient infrastructure, all of which determine the efficacy of crop management [69].

Smallholders face both great opportunities as well as great risks by opting to produce oil palms. Evidence points to oil palm farmers in Southeast Asia receiving a net income that is approximately seven times greater than that of subsistence farmers signaling a transformative change in terms of disposable income and livelihood improvements [55]. On the other hand, the risks that smallholders face are diverse particularly in a scenario involving swings in palm oil prices. According to Vermeulen and Goad, smallholder oil palm producers in Indonesia and Malaysia function either independently, or by sharing production risks with others (namely the government or the private sector) [70]. In the former situation farmers are able to retain all of their profits from sales, but are more vulnerable to financial instability due to price fluctuations and risk poor harvest due to suboptimal seedlings and small plots. In the latter, smallholders are guarded against price shocks and have access to international markets through their linkage with large industry and the government. However, they must forfeit a sizeable portion of their autonomy and flexibility in terms of profits and decisions of how to use their land endowment.

3.2.3. Land ownership issues

Closely linked with the above land sharing arrangements are issues pertaining to land ownership that are often shown to undermine local tenure systems in oil palm plantations. Traditional land tenure institutions are often not legitimized by central or provincial governments that view customary lands as open for commercial production. For forest resources in Indonesia, for example, the process of political decentralization since 1999 has meant that resources that were previously under the management of the Central government have come to be similarly used by local governments and elites [71]. The access and ownership by indigenous communities continues to be limited, as customary land ownership rights remain undermined [72]

These issues seem to have intensified with the recent interest in palm oil biodiesel, and most of the scholarly discussion appears to surround Indonesia and Malaysia [24,37,49,51]. In Indonesia the proliferation of 'nucleus estate' systems (NEs), which function under joint private-smallholder ownership, aim to recognize local land rights as long as they are practiced in designated parcels within a larger private-sector owned parcels. This system, albeit not without its shortcomings, engages the participation of approximately 500,000 smallholders and provides avenues for gaining economic benefits [73]. Through NEs, smallholder farmers allow companies to practice intensive oil palm cultivation on a portion of their land, retaining a smaller portion for their own independent agriculture. In return the company provides a steady customer for the output from the smallholder's own production. Land division between smallholders and companies can be skewed with a 70:30 or 80:20 split in favor of the companies is typical and, as a result, by dealing with a single buyer, the smallholders receive below-market rates for their product [69].

According to the Center for International Forestry Research (CIFOR), "smallholders are often obliged to take out loans to establish plantations and receive limited technical support. The sites allocated are often suboptimal and distant from the community. Social conflict between oil palm companies and smallholders is also common because smallholders enter into price contracts with companies and are not able to benefit from any marked price rises for CPO" [10]. Owing to an incomplete understanding of these furnished contracts and often mistaking the duration of NEs as being short-term, smallholders may enter into such arrangements for immediate economic benefits, without realizing that "such parcels effectively become State land. Farmers may also make decisions driven by short-term gain, selling off land during desperate times at far lower prices than what could be earned through crop yields over the longer term" [69][p.13]

Strides in improving the land ownership by smallholders have been made by the Federal Land Development Authority (FELDA) in Malaysia that was established to diversity agricultural practices and resettle landless communities. As part of the land holding policy by smallholder farmers, individual land titles (including 1000 m^2 of residential area and 40,000 m^2 of plantation land) are granted to settlers once they complete loan repayment [70,74].

3.2.4. Price volatility issues

A final concern relates to the volatility of crude oil, and thus biofuel, markets. As farmers and biofuel enterprises become more connected to global biofuel markets, they become exposed to greater price volatility since oil and petrol prices are generally mirrored in staple commodity prices. According to the World Bank, there is evidence since 2005 of "the pass through elasticity from crude oil prices to agricultural prices increasing from 0.22 for the pre-2005 period to 0.28 through 2009" [75]. By tying agriculture and oil together, palm oil farmers become vulnerable to boom and bust cycles within the global market [76]. Indeed, the past few years seem to confirm these points, and the International Energy Agency has warned that due to rising agricultural feedstock prices, inclement weather, and increased labor costs have all made commodity balances more stringent [77].

4. Future sustainability implications in Indonesia, Malaysia, and Thailand

Several studies have emerged recently cataloguing various biofuel promotion policies and emerging sustainability concerns in major producing nations [36,78–81]. The following review aims to make a unique contribution to this growing body of knowledge by comparatively examining palm oil biodiesel production and consumption in Indonesia, Malaysia and Thailand through the lens of sustainability priorities centered on environmental quality and economic equity. Tables 1 and 2 offer palm oil production and export data as well as biodiesel production and export figures in these three countries, over the last decade, and this section of the

Table 2
Biodiesel production, exports and domestic supply (kilotons).
Source: IEA database – renewables and waste energy statistics.

	2005	2006	2007	2008	2009	2010	2011
Indonesia							
Production	0	21	31	98	311	405	578
Exports	0	15	10	72	178	209	222
Domestic Supply	0	10	39	41	106	199	316
Malaysia							
Production	0	55	130	230	227	95	200
Exports	0	48	95	182	222	90	58
Domestic Supply	0	7	35	48	5	5	27
Thailand							
Production	0	0	60	385	482	516	538
Exports	0	0	0	0	0	0	0
Domestic Supply	0	0	60	342	462	486	547

Table 1
Palm oil production and exports (kilotons).
Source: USDA FA**S**.

	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	July 2012/13
Indonesia											
Production	10300	11970	13560	15560	16600	18000	20500	21000	23,600	25,400	27,000
Exports	6422	7856	9621	11696	11419	13969	15964	16200	16,422	18,000	19,100
Malaysia											
Production	13180	13420	15194	15485	15290	17567	17259	17763	18,211	18,300	18,500
Exports	11650	11602	12684	12931	12900	14644	15485	15530	16,307	16,600	16,700
Thailand											
Production	640	840	820	784	1170	1050	1540	1345	1,288	1,546	1,700
Exports	138	133	81	205	283	360	114	130	382	500	520

paper discusses palm oil trends in each of these countries more comprehensively.

4.1. Indonesia

Surpassing Malaysia in 2008, Indonesia is currently the largest producer of palm oil in the world with total production in 2012 reaching 27 billion tons (Table 1) produced from its roughly 6 million hectares of plantations [82]. Malaysia and Indonesia jointly produce approximately 85% of the total world output of palm oil [83]. As of August 2012, almost all of the biodiesel produced in Indonesia has been derived from crude palm oil. Some small projects have been developed to produce biodiesel from *Jatropha curcas*, a perennial shrub with high oil content that is able to grow on degraded lands and which require little irrigation [83,84]. However, biodiesel from jatropha oil yet to reach commercial scales and palm oil is likely to remain the feedstock of choice until jatropha is able to compete.

Previously a net exporter of petroleum, Indonesia's exploration of biofuels began less than a decade ago. During 2003, even as the international price of crude oil began to rise, national extraction slowed in Indonesia signaling to the government a critical need to rethink its energy strategy [37]. In 2006, the government passed the National Security Act, which called for a diversification of the national energy supply in order to curb the country's strong reliance on petroleum fuels [37]. In the same year, the 5th Presidential Decree set a target to gradually reduce the share of petroleum oil in the country's energy mix from 52 to 20% over a period of 20 years, during which time biofuels were to be developed in order to ultimately contribute 5% [14,83,85]. Subsequently, the Ministry of Energy and Mineral Resources implemented more than a dozen regulations to stimulate biofuel development [14]. The most important of these, the Biofuel Utilization Mandate, has been instrumental in fostering the development of palm oil-based biofuels as it calls for them to account for at least 20% of energy use in the power, industry and transport sectors by 2025 [14].

In pursuing energy security through the propagation of national energy policy, the government sought to develop biofuels by “bringing millions of ‘non-productive’ hectares into production for biofuel feedstock cultivation” [37]. In developing these substitutes for petroleum, the Indonesian government hopes to curb demand for petroleum products, the retail price of which has been heavily subsidized since the early 1970s, and represents a significant drain on the national budget. With the 2006 National Security Act, the government apportioned $1.1 billion of its spending towards the development of the biofuel sector, in particular to support innovation and technology. However, volatile prices of both petroleum as well as palm oil over the last five years have led to regulatory confusion, whereby the support promised in 2006 (when palm oil prices were low) did not materialize in 2007–2008 when palm oil prices spiked [37].

Second to the concern for reducing imports and enhancing energy security, is the prospect of job creation and income increases in rural areas. The original plans for biodiesel estimated “millions” [86] of new jobs in the oil palm plantation sector, new processing plants and village-level NEs that have been discussed previously. Due to decentralization and the different capacities of provincial governments, accounting for a nation-wide impact on jobs specifically through palm oil biodiesel has been irregular. To enhance rural vitality, the NEs scheme planned to set up 1000 villages throughout Indonesia that would be self-reliant on offgrid energy by utilizing of locally grown palm oil biodiesel [87]. According to studies, the NEs scheme has been “implemented gradually, starting from the villages that have been prioritized by the government, state-owned enterprises and the private sector” [88]. The criterion used for choosing and prioritizing villages remains vague. Meanwhile the encroachment of private sector plantations into traditionally owned lands remains a significant threat [51]. Confirming this point, one assessment of three oil palm plantation study sites in West Papua and Kalimantan found that while these facilities benefitted some stakeholder groups, such as companies, investors, and out-growers, they presented challenges to other stakeholders, such as traditional landowners and indigenous communities who became afflicted with “land scarcity, rising land prices, and conflicts over land in all sites.” As that study concluded, “there are some winners but also many losers; and economic gains accrue at the expense of weak rule of law.” [36].

A third concern relates to the high costs involved in subsidizing palm oil-based biofuel production through taxpayer revenues. Dillon et al. estimated that even with the higher petroleum prices of 2008 (and thus higher prices for biodiesel), Indonesia's biofuel blending program cost the government at least $40 million from 2006 to 2008, in addition to a $1.6 billion in funds channeled to the state-owned oil company, Pertamina, over the same period to keep their biofuel development program ongoing [37].

The environmental aspects of palm oil-based biofuels, especially deforestation and illegal logging, remain additional concerns in Indonesia. According to Tan et al., 25% of oil palm plantations in Indonesia are on peat soils, which lead to carbon emissions through oxidation [54]. Indonesia also has the highest deforestation rate globally [47]. Illegal logging poses a perennial threat to Indonesia's rich forest resources while governance mechanisms, which vary across the different decentralized provincial governments, continue to remain inadequate to address associated environmental challenges [50]. The use of armed forces and bribes are common practice by major logging companies and a developing plantation sector energized by a national drive for biodiesel in the presence of governance shortcomings pose several sustainability challenges for the future [37,50]. If palm oil plantations expand production as expected, Indonesia's forest conservation targets will be difficult to achieve, threatening Indonesia's successful participation in REDD+ [89]. Satellite imagery and historical records of land cover from 1975 to 2005 also confirm that palm oil is one of the four largest causes of deforestation in Indonesia alongside logging, agricultural production, and forest fires [90]. A separate study from six independent forest and ecology laboratories and the US-based National Aeronautics and Space Administration concluded that “conversion of tropical forests to oil palm plantations in Malaysia and Indonesia has resulted in large-scale environmental degradation, loss of biodiversity and significant carbon emissions.”[91].

Numerous avenues exist for improving the sustainability of Indonesian biodiesel. In order to deter degradation of ecologically rich forests and reduce impacts from land use change, a primary step towards increasing sustainability would be to allocate future plantations to land areas that are away from forests or are degraded [36]. In terms of policy instruments, the government has put in place the Indonesian Sustainable Palm Oil (ISPO) standard as of March 2011 that is currently being implemented in its initial stages, to be fully rolled out by 2015. Rivaling the more widely known Roundtable on Sustainable Palm Oil (RSPO) – an international consortium of industry, government and research actors that has established voluntary sustainability certification standards – the ISPO is designed to be a mandatory certification for all palm oil producers functioning in Indonesia. Once the ISPO is fully implemented, only then are there plans to use this certification system to create standards for sustainable palm oil-based biofuels. Voluntary standards such as the RSPO do address existing operations, however some biomass certification analysis has suggested utilizing a mix of both voluntary and mandatory

regulation to ensure the sustainable management both present and future plantation practices [92].

To tackle ambiguous land tenure and variable capacities of provincial authorities, reaching an agreement to integrating local and national land ownership rights while designing clear, nationally-enforceable institutions and regulations surrounding land clearing would at once empower rural communities and streamline one aspect of forestry governance across the nation [93].

The problem of uncertainty regarding land issues has been attributed to a dearth of transparency in the forestry sector since at least the 1990s. A lack of transparency has in some ways given way to opportunistic transactions and enhanced the oil palm crop's profitability [10]. Concessions to clear land for growing oil palm monocultures are comparatively easier to obtain than permits to log for timber, inspiring misuse by commercial actors who “use oil palm as a means to gain access to timber. This explains why location permits covering 5.3 million hectares of land for oil palm developments have been issued…while less than 1 million hectares of land have actually been planted with oil palm” [10,94]. No means of taking legal action currently exists against those who denude forest areas without erecting plantations. Unlawful clearing of forests on lands with customary titles damages rural livelihoods. These dual challenges underline a critical need to legitimize indigenous land ownership regulations under a national law to firstly, shield rural livelihoods and develop the aptitude for local governance; and secondly, address the urgent environmental problems that are intensified due to palm oil biofuel development.

Achieving socio economic efficiency is also going to be crucial to biofuel sustainability in Indonesia over the next few decades. Since government support for palm oil-based biofuel fluctuates with commodity prices, any meaningful continual allocation of resources targeted specifically towards sustainability has not yet materialized. Around the time the Biofuel Utilization Act was announced in 2006, Indonesia reduced its fuel subsidies freeing up $15 billion that could then be spent on energy infrastructure and technology [95]. However, only $1 billion was allocated towards biofuel technologies and that suffered inconsistent disbursement as several biofuel related subsidies were not paid out [10]. The socio-economic sustainability of biofuels in Indonesia rests on their efficiency and competitiveness, for which subsidizing the final product (which is already dominated by palm oil) may not be the most optimum decision. Instead, supporting alternate technologies to make second generation feedstock, such as jatropha, or even third generation feedstocks could improve both the environmental sustainability of biofuel production and encourage diversification beyond oil palm.

4.2. Malaysia

The oil palm is crucial to Malaysia's portfolio of biofuel policies. Until recently the country had been the palm oil juggernaut of Asia, and palm oil plantations still occupy about 5 million hectares of Malaysian land, equivalent to almost three-quarters of total agricultural land and about 12% of the country's total land area [68,96]. With a long agricultural history surrounding the oil palm crop, it is unsurprising that palm oil is the nation's top feedstock. In 2000, the Government of Malaysia passed its “Small Renewable Energy Power Program” aimed primarily at capturing the byproducts from palm oil production and converting them to electricity [97] [98]. In 2005, the country established its National Biofuel Policy (BNP) with the primary aspiration of penetrating the world biodiesel market as a leading producer. Through instating the BNP, Malaysia hoped to and succeeded in opening a new export channel for its palm oil biofuel during a time when world prices of petroleum were much higher than those for palm oil [49]. With national biofuels strongly aligned towards palm oil as a feedstock, the BNP aims to establish its use in the transport and industry sectors as a mechanism for rural development and economic growth as well as for exports. This latter emphasis on exports very much eclipsed domestic use of palm oil biodiesel at the beginning of the decade, as is evident from Table 2.

Exports, while still central to Malaysia's aspirations to expand palm oil biofuel until 2011, have also been matched with more domestic consumption that is incentivized by national policies. According to recent estimates from the United States Department of Agriculture Foreign Agricultural Service (FAS), approximately 58% of the biodiesel produced in Malaysia in 2013 was used domestically while 43% was exported to Singapore, Australia the EU, among other destinations [99]. Exports, however, are projected to remain influential for current and future production, impacted by both national export policies as well as the biofuel import policies in importer nations.

Policies implemented by major trade partners like the EU towards biofuels and biofuel feedstocks have had a large influence on Malaysia's palm oil export opportunities. In 2003, before the BNP was established in Malaysia, the EU declared a fuel consumption target under its Directive 2003/30/EC under which biofuels were to eventually replace 5.75% of all of its transport fuels by 2010 [49]. The EU created a mandate in 2009 (Directive 2009/28/EC) requiring that 10% of its transport fuel consumed in 2020 be met from renewable sources, mainly biofuels. With this mandate in place, it was estimated that more than 10 million tons of biofuels would be required to meet the growing demand and “imports would serve around 20% of the biofuel production. About half of them would be first generation feedstock and mainly oilseeds” such as palm oil [100]. Quick to take advantage of this export opportunity, Malaysia ramped up its production of palm oil and began exporting large volumes of both palm oil as a feedstock.

However, this trade has been threatened by several developments. The EU implemented new sustainability criteria in 2011 that effectively de-list palm oil biodiesel from Malaysia as qualifying for its quotas and support policies [101]. In anticipation of a possible fall in exports to the EU, Malaysia is currently working towards building up the market in the United States and “laying the foundation for palm oil to qualify as an advanced biofuel source in the United States under its Renewable Fuels Standards” [101]

In addition to export opportunities, Malaysia's promotion of palm oil biofuel is also directed towards rural development and creating employment. Towards this aspiration, Malaysia has achieved mixed results largely due to the interaction of petroleum and palm oil prices. After the BNP was implemented in 2005, the Malaysian government distributed 92 approval permits for new palm oil biodiesel projects that, once completed, would have the combined capacity to produce 11.7 billion liters of fuel per year [98]. These plants have generally been quite profitable, with a typical 50 kt biodiesel production plant in Malaysia yielding a positive return on investment within 3.5 years [102]. However, at the end of 2007 and the beginning of 2008, the energy-equivalent price of palm oil rose beyond that of crude petroleum, the refined products of which enjoy generous subsidies in Malaysia, thereby shutting production at many biodiesel plants and destabilizing plans for new facilities [54]. At the beginning of 2010, the international price of palm oil had fallen enough relative to the price of crude oil that most biodiesel plants re-opened and plans for several new plants had been announced [101]. Labor resource figures in the palm oil industry indicated the employment of over 800,000 workers in 2008 [98]. However, the incremental increase in employment in the palm oil sector as a result of biofuel development remains difficult to identify separately.

There are several ways that Malaysia could better ensure social and environmental sustainability in its palm oil biofuel industry. In terms of social sustainability, unclear land ownership rights remain a problem that has generated strife due to industry advances into traditional lands [51]. Contracts and communal agreements between producers and farmers have been criticized for their insufficient clarity, transparency and lack of coordination [98]. The Malaysian palm oil industry is strongly vertically integrated, which gives it substantial power to influence policy. Lopez and Laan ([49], p. 33) have noted that “there has been significant consolidation of corporations in the Malaysian agriculture sector as well as expansion in terms of land banks and diversification towards other areas of the trade chain” [49]. Within the status quo, smallholder palm oil producers are to be expected to remain marginalized with growing instances of encroachment on indigenous lands due to a de-culturalization of production practices that are insensitive to customary rights and leave smallholders susceptible to patronization by large industry players [49,70].

Indeed, a strategy that fosters decentralized production in rural areas might achieve better equity in production and ameliorate the power imbalance apparent between rural farmers and large industry. As expressed by the U.S. Agency for International Development (USAID) “decentralized energy using non-food crops can reduce soil erosion, improve soil fertility, improve water quality and reduce deforestation with careful planning and management. Biofuels on a smaller, decentralized scale can provide energy for cooking, transport and lighting” [103]. Examples of decentralized biodiesel production are scant in Malaysia, but can be found in other areas of Asia, where they have helped increase rural incomes [103].

Environmental sustainability in Malaysia is a secondary government concern despite criticism by civil society groups of the country's palm oil industry. For example, one assessment noted that “the presumed environmental benefits of biodiesel—most notably in terms of reducing greenhouse gas emissions—have evaporated with improved understanding of the full lifecycle impacts of biofuel production … The expansion of the palm oil industry in Malaysia has been associated with deforestation, release of carbon from vegetation and soil, forest fires, soil erosion, water pollution and biodiversity loss.” [49]

Part of the explanation underlying unsustainable production techniques is the fragmented nature of Malaysian energy policymaking. With a decentralized government, achieving environmental protection and executing Environmental Impact Assessments (EIAs) of existing and planned biofuel production systems, falls under the jurisdiction of the different Malaysian states, which have variable capacities for governance of the country's rich ecological heritage. Most notably the Eastern Malaysian states of Sabah and Sarawak are exempt from most national policies and standards and can set their own regulations [97]. Malaysian forests are a globally vital biological hotspot [47]. And palm plantations are estimated to retain only about 20% of a forest's habitat value [51]. These environmental tradeoffs between plantations and forests have attained global attention and elicited copious censure from international environmental NGOs. Still, in Malaysia environmental preservation appears to be a comparatively lesser national consideration in planning future biodiesel projects.

Environmental considerations are beginning to infiltrate private sector production decisions through initiatives such as the RSPO which engages private sector, environmental and farmer groups. With voluntary membership, the RSPO has drawn up sustainability criteria and established a certification scheme in the hope of enabling palm oil consumers to be able to make informed choices. However, because the scheme is voluntary, its effect may simply be to divert certified palm oil towards consumers in countries with high sustainability standards, leaving production that does not meet the standards to be sold elsewhere Similar to Indonesia, the Government of Malaysia is expected to implement its own national sustainable standard, the Malaysian Sustainable Palm Oil (MSPO) criteria by 2014 [104].

4.3. Thailand

According to the U.S. Foreign Agriculture Service, Thailand is currently the third leading producer of palm oil in the world with 2012 figures reaching 1700 kt (Table 1). Even though Thailand produces less palm oil than Indonesia or Malaysia, a much higher proportion of its palm oil is converted to biodiesel. In 2007, Thailand's total biodiesel production was just 60 kt (kt). Within four years, however, it climbed to 538 kt, in par with Indonesia (578 kt) and well past Malaysia (200 kt).

Palm oil biodiesel in Thailand has risen in significance in the last decade due to a number of government driven initiatives aimed at improving energy security, enhancing employment opportunities and promoting rural development [105]. Government support for palm oil biodiesel has targeted both supply and demand.

Although several programs have existed since 2005 to encourage both ethanol and biodiesel production as a means of energy diversification and reducing reliance of fossil fuel imports, in 2008 palm oil-based biofuel production received a boost through the creation of government issued mandates [4]. Biodiesel is produced as 100% palm oil derived fuel or B100, that is then blended with diesel in various proportions. Thus petroleum diesel mixed with 2%, 3%, 5% and 10% biodiesel is marketed as, respectively, B2, B3, B5 and B10. In its Biodiesel Development Plan 2008–2022, the Ministry of Energy mandated the domestic use of B2 in 2008, and the later raised the blending level to B3 in 2010 [4]. These mandates resulted in a close to fifteen-fold increase in biodiesel production from 2007 to 2013 [4].

In addition to the implementation of mandates, government supply-side and demand side support for national palm oil biodiesel has also swelled in the last decade. Since the adoption of the two National Alternative Energy Development Plans (2004–2011 and 2008–2022) with the explicit aim of reducing dependence on petroleum imports, demand- and supply-side policies have included “production mandates, tax privileges from the Board of Investment (BOI), tax and retail price incentive, R&D support, public awareness promotion” [4] and others. Incentives have targeted all parts of the supply chain from farmers to refineries. To encourage palm oil production the government has subsidized crop prices and extended low-interest loans to help oil-palm farmers increase their productivity. With a biodiesel consumption target of 3100 million liters in 2012, the Government expects the country to reduce its petroleum import bill by approximately $675 million every year [106,107]. As of January 1, 2012 the government has instated a compulsory blend for biodiesel is B5 in Thailand as a result of which, domestic consumption in 2012 reached 850 million liters with 2013 numbers expected to reach 890 million liters [4].

To meet future demand projections, in 2005 the Government articulated a three-part plan to ensure adequate domestic biodiesel supply, mainly involving the expansion of oil-palm plantations over the next ten years. The Cabinet allocated approximately $34 million in low-interest loans to farmers. Through the loans, the Committee on Biofuel Development and Promotion (CBDP) planned to both expand the planted area and to meet its goal of an average yield of 20 t/ha [4]. Although production shortfalls were a concern in 2010, 2012–2013 supply of crude palm oil is projected to be sufficient to meet domestic demand. In addition, the government intends to rent close to 0.2 million ha of land as

oil palm plantations in neighboring countries to add 440 million liters per year to domestic biodiesel production capacity [107].

The strong growth of Thai palm oil biodiesel production, and consumption, presents both opportunities and challenges for sustainability. Two factors make Thailand more likely to meet social and environmental sustainability than its neighbors: its pattern of ownership and its cultivation choice. Most of the oil palm plantations in Thailand are cultivated in its southern provinces, which is also the location for a majority of the country's oil mills and facilities. According to national sources, "over 90% of plantations in the country are owned by small farmers"[108] which is far greater than the share of smallholder production in Malaysia and Indonesia. As a result of local ownership, a majority of the plantations exist on marginal land areas and old rubber plantations, reducing (albeit not completely cancelling) the need for clearing forested areas [107].

In terms of challenges, pursuing a strategy to further expand palm oil plantations nationally is likely to aggravate ecological fragility by encroaching upon forested areas. Unless oil palm cultivation techniques used to expand production to these areas become more conducive to supporting habitats and enhancing biodiversity, displacing biologically rich forested areas in neighboring countries makes little environmental sense [109,110]. The negative externalities posed by plantation style agriculture can be addressed and mitigated by growing crops on marginal and degraded lands, intercropping fuel crops with others, using natural gaps in forest areas and reducing the need for commercial fertilizers, to name just a few well-known mechanisms of sustainable agriculture. Moreover, simply expanding oil palm plantations further entrenches the sole reliance on palm oil for biodiesel and undermines the energy security principle of diversification. Jatropha is one form of available feedstock, but production rates are still too small for making commercial biodiesel [83]. Coconut oil is also another option, however, it fetches a significantly higher price than palm oil, and hence the opportunity cost of turning it into a diesel fuel is high. By still being at a nascent stage of biodiesel development, Thailand has a unique opportunity to explore the suitability of alternate feedstocks and break the dependence on first-generation sources of bioenergy.

5. Conclusion

Our review culminates in three main policy recommendations. First, to address environmental sustainability it appears that the successful implementation of national and international standards for oil palm plantations that are enforceable is a key priority. Reliable compliance with these mechanisms could be vital to environmental conservation, enhancing the preservation of areas of critical ecological value and avoiding the obliteration of rich carbon sinks such as peat soils if they are able to target degraded lands for future plantations

Second, to sustain rural livelihoods, it is vital to recognize and reconcile traditional land use rights and reach a system that clearly demarcates areas under traditional and state ownership. Along the same lines, encouraging more opportunities for decentralized, small-scale production of fuels by smallholders is likely to extend the income benefits currently available to rural producers.

Third, encouraging the development of new biofuel technologies is an imperative to future sustainability. Government support should go towards developing biodiesel technologies that use different feedstocks and enhance efficiency of production methods, in order to avoid the shifting of total dependence from petroleum oil to palm oil.

As the examination of the Indonesia, Malaysia and Thailand cases have shown, effort is needed in order to enhance ecological stability and socioeconomic equity in developing palm-based biodiesel. Prioritizing sustainability in Indonesia would require encouraging future plantations on non-forested, degraded lands, the recognition and legitimization of customary land tenure, designing enforceable institutions surrounding ecological conservation and land clearing for feedstock cultivation, and boosting competition and efficiency by reducing end-product subsidies. Greater sustainability in the case of Malaysia would mean enhanced government involvement in developing and enforcing sustainability criteria such as the proposed MSPO, and more emphasis on decentralizing production in order to realize equitable benefits and rural development gains. In Thailand, sustainability of current practices can be improved by protecting local ownership of plantations, encouraging cultivation on marginal, degraded lands instead of ecologically sensitive forests and exploring alternate feedstock for biodiesel production. In all three cases, opportunities to meet sustainability goals need to be urgently explored and acted upon before trends counter to those goals become deeply entrenched and in some cases, irreversible.

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